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STABILIZATION OF MUNICIPAL REFUSE BY COMPOSTING

by P. H. McGauhey, M. ASCE
and Harold B. Gotaas, M. ASCE

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STABILIZATION OF MUNICIPAL REFUSE BY COMPOSTING

P. H. McGauhey and H. B. Gotaas
University of California

SYNOPSIS

The essentials of aerobic composting to stabilize municipal refuse developed during more than two years of research into the practice and fundamentals of composting are presented. Composting processes used throughout the world are briefly reviewed.

Composting is a natural biological process which proceeds most rapidly under thermophilic aerobic conditions. The principal environmental factors which govern the speed and course of the process are shown to be moisture content, aeration, particle size, and initial carbon-nitrogen ratio. Seeding is shown to be unnecessary, and hydrogen ion concentration to be an unimportant factor in composting municipal refuse.

Important steps in composting refuse such as segregating, grinding, stacking, turning, and remilling are discussed, along with operating factors and the judging of the condition of a compost on the basis of observations, course of temperature, and control tests. The time required for stabilizing several types of refuse material by various processes is shown, as is the merit of finished compost as a fertilizer and soil conditioner. The problems of practical municipal composting are reviewed. It is concluded that composting offers an economical and sound solution to the refuse disposal problems of many communities, at the same time reclaiming organic material of great value to agriculture.

INTRODUCTION

In a broad sense composting refers to the production from organic matter, through the agency of microorganisms, of a relatively stable humus which may beneficially be used on agricultural soils. For many centuries it has been practiced in a simple form by individuals and village groups wherever vast populations have maintained themselves for long periods on limited areas of tillable land. The processes of composting exist in nature; however, attempts to systematize and commercialize composting are principally a development of Europe and Asia of the past twenty-five years for the purpose of increasing food production or maintaining soil fertility.

Because of the enormous capacity of the United States to produce food by applying inorganic fertilizers to its relatively virgin soils, interest in composting has until recently been confined principally to individual gardeners and to a few entrepreneurs more interested in selling patented processes and devices than in producing and marketing compost. These attempts at selling composting have often been surrounded by mysticism and secret formulae and may have actually retarded commercial development and production of useful compost. The present widespread serious interest in composting in the United

States is the result of a new concept of the process as a device for the disposal of municipal refuse.

The need for a new method of refuse disposal in many municipalities is acute. Some communities which have endured overlong the nuisance of open dumps or rudimentary landfills now face the problem of financing immediately a generation of delayed progress. Other communities face a variety of refuse disposal problems—landfill sites are being overrun by subdivisions; new landfill sites are excessively expensive or non-existent within economic haul distances; and incinerators are expensive and difficult to locate in the community. Then, too, a new set of considerations are complicating the problem of refuse disposal in many areas. These include the contamination of ground waters by leachings from dumps and fills, and the pollution of the air by gases and particulate matter from burning or incineration.

Any new process for disposing of municipal refuse should be free of the health hazards and nuisance aspects of dumps; require smaller area than the landfill; cost much less than an incinerator to install; and involve a rapid, sanitary, reliable, and economical procedure. The possibility that composting represented such a process created a great interest in it and led to the research into its fundamentals on which this report is based.

Composting Processes

Composting processes may be divided into two general classes—those in which the stabilization achieved is principally the result of anaerobic decomposition of organic matter; and those in which aerobic decomposition predominates. Strictly speaking, the latter process is carried out by facultatively aerobic organisms requiring only a modest amount of atmospheric oxygen but the rapid rate of decomposition, the freedom from odors, and the degree of stabilization achieved are so characteristic of aerobic decomposition that the process is called "aerobic" in contrast with the slow, odorous, and somewhat less complete stabilization characteristic of the "anaerobic" process.

Most of the older traditional composting procedures are anaerobic. The more primitive methods long used in the Orient involve placing miscellaneous organic matter, including night soil and animal manures, in open piles or pits and allowing 8 to 12 months for composting. This procedure was systematized in India some 30 years ago by Lord Howard (1), and widely used since then in that country, as well as in South Africa during World War II. The practice is to pile on the ground or in pits to a depth of some five feet or more alternate layers of putrescible materials, such as garbage, animal manures, night soil, and sewage sludge, and more stable matter such as leaves and straw. The mass is usually turned twice during a 6 to 8-month composting period and drainage liquors may be recirculated. In Africa and Australia holes are punched in the pile with sharpened sticks in a not too successful attempt to admit sufficient air to prevent anaerobic conditions inside the pile.

In Europe the refinement of ancient composting practices took the form of mechanization of the process. During the decade 1920-1930 various closed cells were designed and patented. Most important are those developed by Beccari (2) in Italy and by Verdier (3) in France. The Beccari cell incorporates air vents which are opened to afford some minor degree of aeration of a charge of organic matter after it has undergone an initial period of anaerobic decomposition. Verdier added provision for recirculating gases or drainage liquors.

Both open piles and closed cells have been used in Europe in various composting operations intended to be aerobic. In 1931 Jean Bordas (4) of France patented a batch composter in the form of a silo divided by a grate into an upper and lower section, with provision for introducing air along the walls and through a central pipe. There seems, however, to be no reports of its successful operation. In 1932 the V.A.M. (Refuse Disposal Co.) of Holland (5) began what is now the most extensive composting enterprise in the world. The process is essentially an adaptation of the Indore process to the composting of municipal refuse other than garbage. As originally practiced it involved dumping refuse in long high piles with no treatment other than periodic sprinkling with recirculated drainage liquor. In a more recent installation refuse is ground in a special mill, then placed in open piles and sprinkled and turned from time to time during a 3 or 4-week composting period. In Denmark and Sweden refuse is ground by the Dano process before composting in open piles under either anaerobic or aerobic conditions, depending on the subsequent handling of the material.

When interest in composting in the United States began to be taken seriously as a method of refuse disposal it was soon apparent that practices elsewhere in the world were not readily applicable. The Indore process involved too much hand labor as well as the use of animal manures; a few installations of the Beccari process had already been constructed in the United States and abandoned because of unsatisfactory performance; and in any event the slow anaerobic processes involved were not well suited to American needs. All methods advocated in the United States involve aerobic decomposition although none has yet been put on a commercial basis utilizing mixed refuse on a municipal scale. The four methods most seriously considered are to be discussed on the program today. It is sufficient to state here that the Frazer-Eweson (6) and Earp-Thomas (7) procedures make use of closed cells or digesters, while the Compost Corporation of America and the University of California use open piles.

Experimental Investigation

In 1950 the Sanitary Engineering Research Laboratory of the University of California began a study of composting (8) as a possible solution to urgent problems of refuse disposal aggravated by California's explosive growth in population. From a study of the literature it soon became evident that composting had developed as an art rather than as a science and, consequently, like most ancient arts, was surrounded by a haze of misconceptions concerning its fundamentals. For example, a number of processes had been patented based on the application of forced air to sustain aerobic decomposition and at the same time on the recirculation of drainage liquors which develop only under anaerobic conditions. Other things reported by many to be essential to successful composting included seeding with manure, inoculation with special organisms, recirculation of liquids or gases, forced aeration, and the addition of "enzymes and hormones." Established principles of organic decomposition were found throughout scientific literature, but little significant work had been done on their application to the composting of municipal refuse. It was, therefore, necessary to carry out research studies to establish the fundamentals of composting before it was possible to develop a procedure.

For convenience, flexibility, and control of variables, experiments were first conducted on a laboratory scale. Knowledge gained and procedures developed during these studies were then applied to larger scale pilot and field scale studies in order to adapt them to practical composting.

Laboratory studies of organic material were made in 5-gallon jars and 55-gallon drums in a high temperature laboratory. Materials composted included shredded vegetable trimmings composted alone or in various combinations with such materials as straw, horse manure, shredded paper, oyster shell, and garden soil. Pilot scale studies were conducted on similar materials in 40-inch square bins holding about 1-1/2 cubic yards and located in an unheated warehouse. Field scale studies were run at the Berkeley refuse disposal site on thirteen different 2 - 3 ton loads of combined city refuse from eleven different districts of the city. In addition, city refuse was composted in combination with raw sewage sludge, with digested sewage sludge, with pear wastes, and with garden soil. The material was shredded in a hammermill and composted in open piles.

Basic Considerations.--Because composting is a biological process, environmental factors influencing the activities of microorganisms determine the speed and course of the composting cycle. In general, such factors include seeding, moisture content, aeration, hydrogen ion concentration, temperature, and particle size and initial carbon-nitrogen ratio of the food material.

Seeding.--Many proposals for commercial composting are built around the use of some special inoculum known only to its discoverer, who claims it to be fundamental to successful operation of the process. Others prescribe the use of horse manure in quantities up to 30 percent of the total mass, or the addition of "garden soil," or the recycling of partially composted material to seed the raw refuse. Inasmuch as the success of a process as well as its economy is involved in the matter of seeding, early studies were made to evaluate this factor. Chemical and bacteriological tests were sufficient to show that several commercial preparations were worthless. Others were studied by controlled laboratory and pilot scale experiments. A number of studies were made using various amounts of horse manure as the seeding material. In all cases it was obvious that moisture and aeration were far more important factors. No significant increase in the rate of buildup of bacterial population resulted from the use of 30 percent horse manure in a typical garbage material. Both seeded and unseeded composts reached temperatures at the top of the mesophilic range within 24 hours.

When increase in percentage ash, decrease in carbon, and decrease in carbon-nitrogen ratio during the composting period (criteria for degree of decomposition) were used as indicators of the value of seeding with a reasonable amount of horse manure, no significant benefits were observed. Table 1 is typical of the results obtained.

Two studies were made using commercial additives. The first involved a "starter" and was made in the high temperature laboratory. Two 55-gallon drums were filled with identical mixtures of shredded leafy vegetables and dry hay. To one was added the "starter" in the amount specified by the manufacturer. Both were aerated in the same manner and both produced a satisfactory compost, with no discernible benefit from the additive.

The second investigation made use of a highly promoted secret inoculum. Half a ton of an identical mixture of shredded vegetable trimmings and paper was placed in each of two bins. The material in one bin was sprayed and thoroughly mixed with a suspension of the inoculum in accordance with the directions of the manufacturer. The material in both bins was turned daily and both produced a good compost in 19 days. The lack of merit of the inoculum is strikingly illustrated by the similarity of the temperature curves in Figure 1.

TABLE 1

ANALYSIS OF SEEDED AND UNSEEDED COMPOSTS

Material	Days after start of experiment	Percent Ash	Percent Carbon	C/N Ratio	pH
Shredded veg. trimmings	0	10.9	42.0	20.2	6.2
	2	14.1	21.8	11.4	5.2
	8	17.8	35.5	10.8	9.1
Shredded veg. trimmings plus 2% horse manure	0	10.9	42.0	20.2	6.2
	2	12.9	38.4	21.2	4.6
	8	20.1	37.4	18.6	8.8

Chemical analyses made during the composting period and shown in Table 2 further illustrates the unimportance of the inoculum.

TABLE 2

ANALYSIS OF UNINOCULATED AND INOCULATED COMPOSTS

	Initial	Third day		Final (nineteenth day)	
		Uninoculated	Inoculated	Uninoculated	Inoculated
Ash %	10.51	13.8	16.12	29.18	28.86
Moisture %	90.18	80.67	79.38	74.74	75.07
Carbon %	37.75	38.59	41.67	31.87	31.41
Nitrogen %	2.16	2.27	2.30	1.95	1.91
Phosphorus %	0.17	0.25	0.31	0.31	0.33
Potassium %	1.00	0.93	0.81	1.08	1.10
C/N ratio	17.5	17.0	18.0	16.2	16.5

Inasmuch as the inoculum was purported to be a special culture of bacteria high in thermophilic actinomycetes it was compared with rich garden soil and a poor agricultural soil with the results shown in Table 3.

Other experiments demonstrated that the addition of soil or the recycling of composting material did nothing to alter the speed on the course of a compost. From these studies and similar results by other observers it was concluded that both mesophilic and thermophilic microorganisms indigenous to refuse are sufficient to carry on the composting process with great rapidity when environmental conditions of moisture and aeration are suitable.

Subsequent success with numerous composts bear out the fact that seeding is not an essential part of a practical process for composting municipal refuse.

TABLE 3

COMPARATIVE NUMBER OF THERMOPHILIC ACTINOMYCETES IN VARIOUS MATERIALS

Material	Organism count per gram of material
Inoculum	15.8×10^7 colonies
Rich Soil	13.4×10^7 "
Poor Soil	15.8×10^6 "
Horse Manure*	15.0×10^7 "

* As reported by Waksman (9)

Hydrogen Ion Concentration.--Inasmuch as hydrogen ion concentration can be an important factor in biological processes, experiments were run to determine what benefits if any might result from the addition of a calcium carbonate buffer. Various amounts of calcium carbonate were used. The result was a very slight reduction in the normal pH sag shown roughly in the final column of Table 1; a slightly greater degree of decomposition as indicated by increase in percentage ash after correction for the added calcium carbonate; an improved physical appearance of the final product. On the other hand, a serious loss of nitrogen occurred in buffered samples and composting time was not shortened. The experiments and subsequent experience in composting demonstrated that the addition of calcium carbonate to a compost is of doubtful value, and that pH control is not necessary in the composting of garbage, municipal refuse, and other mixtures studied during the research investigations.

Moisture.--Moisture content is one of the most important factors in aerobic composting. Too low a moisture content deprives microorganisms of the water needed in their metabolism and consequently inhibits bacterial activity. At too great a moisture content water displaces air in the interstices between particles, giving rise to anaerobic conditions with attendent putrefactive odors, foul drainage liquors, and retarded decomposition.

The maximum amount of moisture permissible varies with the nature of the material to be composted, especially with its ability to maintain structural strength when wet. In the laboratory and field studies it was possible through aeration by daily turning to compost mixtures of vegetable trimmings and straw having initial moisture contents up to 85 percent, while 76 percent initial moisture was too great when paper was used instead of straw. Municipal refuse was composted at moisture contents from 30 to 75 percent, although it was difficult to prevent some degree of anaerobiosis when moisture exceeded 70 percent. The moisture content of municipal refuse, under normal conditions, properly shredded without pulping, may generally be expected to fall within the 40-60 percent range found most suitable for composting.

Excessive moisture may be reduced by additives such as straw, dry soil, or dry sawdust if the amounts necessary do not greatly increase the carbon-nitrogen ratio and thus unduly prolong the composting period. Paper was found to be quite ineffective in controlling moisture. Frequent turning seems to be the most desirable method of moisture control, as it promotes loss of moisture by evaporation without disturbing the C/N ratio, and at the same time acts as an effective aerating procedure. If moisture content gets too low, turning permits effective adding of moisture during the process.

The foregoing considerations concern high initial moisture content. There is evidence that material being composted in the open may become excessively wet if rainfall is heavy, necessitating the use of preventative measures such as shed roofs or special shaping of the piles. Observers in both Scotland and South Africa report soaking of compost piles by relatively continuous heavy rainfall, although intermittent heavy rains did no harm. One heavy rain was experienced during the Berkeley field studies. It penetrated open compost piles with rounded tops only to a depth of from 1/8 to 1/4 of an inch.

Aeration.--As previously noted the amount of atmospheric oxygen required to prevent typical anaerobic decomposition from developing is not great. Nevertheless some air must be supplied if rapid, nuisance free composting is to be achieved. Methods proposed include periodic turning of the material, forced air, and the use of chimneys or other openings through the pile. Experiments with both bins and open piles showed turning to be most effective. Forced air did not satisfactorily penetrate masses of moist material, and when introduced through adequate diffusers it proved both expensive and prone to cause excessive drying. Water sprayed on the pile to overcome drying did not penetrate to any extent and the disturbing of the pile necessary to add moisture constituted in itself adequate aeration. This and other evidence indicates that aeration of material in closed digesters by forced air would be both difficult and expensive, if not impractical. Chimneys and holes penetrating the composting mass proved totally ineffective, producing at best only a minor local zone of aerated material in a large putrefying mass.

Temperature.--Except for very small masses such as might be used in laboratory experiments there is no need for temperature control when material is composted in open piles in moderate climates. In cold climates it seems probable that an outer shell perhaps 6 to 12 inches in thickness might remain quite inactive and serve merely to insulate the composting material within the pile. When turned into the interior of the pile, this shell might introduce a thermal shock and result in a lengthening of the compost period.

The temperature in an aerobically composting mass follows a typical curve. Consequently temperature becomes an important control test and an aid to judging the course of a compost. The handling of material involved in placing it in a compost pile brings its temperature close to that of the ambient temperature of the surrounding air. If other environmental conditions such as moisture and aeration remain suitable mesophilic organisms indigenous to the refuse multiply rapidly, their metabolic processes giving off heat which escapes but slowly because the pile is to a large degree self-insulating. The result is a rapid rise of temperature to 45 or 50^{o}C which represents the upper limit for mesophilic organisms. At this temperature, however, the environment becomes optimum for thermophilic microorganisms and if moisture and aeration remain proper, their rapid growth and activity causes a further rise of temperature to 70 or 75^{o}C—or to a level where excess temperature limits bacterial populating. The high temperature then persists for a time

until food supply becomes the limiting factor; that is, until the stabilization of the organic matter is well advanced. After that the temperature of the mass declines and the compost is considered finished in that it may be stored for long periods without any new generation of heat or appreciable chemical change, although slow bacterial activity may continue for a long time.

In a small mass of composting material there is a typical temperature plateau as the mesophilic bacterial population declines and the thermophilic population develops. Figure 2 illustrates a typical case of the successive development of populations and rapid rise of temperature to 75°C during the first 3 or 4 days.

The study from which Figure 2 was made involved a compost of vegetable trimmings and straw in a 40-inch square bin. It is notable that although the ambient air temperature was but 10°C, temperatures of more than 60°C persisted for a number of days within two inches of the exposed surface of the pile. The large decline in temperature beginning on the fourth day illustrates the result of the onset of anaerobic conditions due to lack of aeration.

A quick recovery of aerobic conditions is signalled by the rise in temperature following aeration by turning on the 5th day. Another decline set in as the material again became anaerobic, recovering once more on turning. Successively lower maxima and a final decline in temperature indicated that stabilization was approaching completion. The lower temperatures recorded at mid-depth of the pile indicate that in a situation where aeration is critical bacterial survival is greatest near the surface where diffusion of atmospheric oxygen adds a small increment.

In large piles where heat loss from the interior of the pile is slow the temperature curve does not hesitate at the transition from mesophilic to thermophilic organisms. Figure 3 is typical of aerobic composting as observed in the Field Studies. Here the temperature rose rapidly to a maximum in four days and slowly declined. In many other studies the high range of the curve remained quite flat for 4 or 5 days. After that the temperature dropped rapidly as stabilization progressed.

Carbon-Nitrogen Ratio.--To be economically feasible as a method of refuse disposal composting must produce a product which can be sold for use on agricultural land. Consequently the ratio of carbon to nitrogen in the finished product becomes a matter of importance. The C/N ratio of the raw material is likewise important as the time required for composting organic matter depends upon it. From the initial and final values the change in C/N ratio during the process can be found. This change is normally indicative of the degree of decomposition and hence is more significant than the absolute value of the final ratio in judging the fitness of a compost made from material higher in paper or ligno-cellulose for use on growing crops.

Living organisms utilize about 30 parts of carbon for each part of nitrogen, hence an initial C/N ratio of 30 would seem most favorable for rapid composting. Various researchers have reported the optimum value as being between 26 and 31. Material with initial C/N ratios of from 20-78 was composted in the University of California studies. From the results an initial C/N ratio of 30 to 35 can be recommended as optimum for rapid composting of municipal refuse without loss of nitrogen. Above that range, composting time can be expected to increase with C/N ratio; below that range rapid composting is likely to be accompanied by an increasing loss of nitrogen.

The optimum C/N ratio for composting is not, of course, the optimum C/N ratio for the soil. A value of 20 has been widely accepted as the upper limit

at which there is no danger of robbing the soil of nitrogen. The availability of the carbon, however, seems the most important factor and C/N ratios higher than 20 are acceptable when the carbon is not readily usable by bacteria. Humus resulting from composting has often been reported as having a C/N ratio of from 10 to 20. Such values may be obtained by composting garbage alone but may not result from composting mixed municipal refuse even though a high degree of stabilization is achieved.

Table 4 (on page 10) lists the reduction in C/N ratio achieved in a number of the pilot plant and field tests which yielded good finished compost, together with the accompanying change in percent nitrogen. Studies No. 1 to 8 were made on vegetable trimmings with various additives while Studies No. 9 to 20 were made on municipal refuse from the City of Berkeley.

The profound changes in C/N ratio observed in Studies No. 8, 18, 19, and 20 and shown in Table 4 represent the conversion to carbon dioxide of readily available carbon in the garbage component of the refuse. The remaining carbon, although sufficient to cause a high C/N ratio, represents material such as paper which is much more resistant to bacterial decomposition.

Essentials of Composting

The process for composting municipal refuse which can be recommended as a result of these studies involves segregating, grinding, stacking, turning, and regrinding the refuse; and requires a knowledge of how to control and judge the process on the basis of observations and laboratory tests.

Segregation of Refuse.--An appreciable portion of municipal refuse is material which is not subject to bacterial decomposition and must be removed somewhere in the process before compost is placed on agricultural soils, unless it is ground into small particles. Table 5 shows the percentage of various compostable and non-compostable materials found in approximately 30 tons of mixed municipal refuse from all sections of Berkeley, California.

Inasmuch as grinding is an essential step in the composting process some degree of segregation of non-compostable items seems inescapable. Rags and non-ferrous metal objects are of sufficient value to justify removing them by hand picking as refuse moves along a conveyor belt. Tin cans and ferrous metals may be taken out by a magnetic separator. The Compost Corporation of America estimates that in a large scale operation this material as well as glass would represent profitable salvage (10). Ceramic objects are perhaps the greatest nuisance as hand picking is expensive and devices capable of pulverizing such material while at the same time shredding paper and garbage are not available nor easy to design.

Grinding or Shredding of Refuse.--Grinding or shredding of raw refuse produces a number of beneficial results which hasten decomposition. The material is rendered more susceptible to bacterial invasion through exposing greater surface to attack and destroying the natural resistence of vegetation to microbial invasion. In addition, the material is rendered quite homogenous, given a beneficial initial aeration, and acquires a structure which makes it more responsive to moisture control and aeration as well as easier to handle.

There is no special size requirement but the material must not be pulped lest it become too soggy to compost. The pilot plant studies were conducted satisfactorily on material chopped into pieces about one inch across by means of a John Deere roughage mill. A hammermill was used

TABLE 4

RELATION OF INITIAL C/N RATIO TO TIME REQUIRED
FOR STABILIZATION, FINAL C/N RATIO, AND CHANGE IN NITROGEN

Study No.	Composting Time Days	Initial C/N Ratio	Final C/N Ratio	Change in % Nitrogen	Remarks
1	7	21.0	12.1	+0.60	
2	8	18.5	12.2	+0.53	
3	16	24.9	14.1	+0.80	Became anaerobic
4	10	20.2	10.8	+0.27	
5	10	34.6	26.4	+0.06	
6	14	27.7	20.5	+0.08	
7	16	40.2	20.1	+0.32	
8	17	54.6	22.8	+0.54	High paper content
9	12	19	14	-0.06	
10	14	20	19	-0.11	
11	14	22	19	-0.11	
12	16	28	19	-0.01	
13	14	31	20	+0.11	
14	14	30	19	+0.01	
15	16	32	20	-0.29	
16	14	33	19	+0.44	
17	15	35	24	+0.11	
18	16	50	24	+0.45	High paper content
19	16	51	22.7	+0.33	High paper content
20	21	78	35	+0.36	High paper content

TABLE 5

PHYSICAL ANALYSIS OF MUNICIPAL REFUSE
AT BERKELEY, CALIFORNIA

% Tin Cans	% Bottles, broken glass	% Rags	% Metals	% Inorganic wastes,* no value	% Compostable material
9.8	11.7	1.6	0.9	7.6	68.4

* Broken ceramics, concrete, plastics, etc.

on municipal refuse in the field study on Berkeley refuse. On the basis of that experience a minimum screen size of 1-1/2 inches is recommended. Wet grinding has been used to overcome the extreme abrasiveness observed when refuse is ground just as it comes from the collection vehicle, but the resulting mass is too wet for aerobic composting. One of the most serious deterrents to commercial composting at the present time is the lack of grinding equipment especially adapted to shredding refuse.

Stacking Shredded Refuse for Composting.--Shredded refuse to be composted in the open is placed on the ground or on a paved area in piles or windrows. For reasons of space economy and ease of handling, windrows are the most convenient. They may be of any appropriate length or width, but the height is somewhat critical. If the pile is too high the material will be compressed by its own weight, losing pore space and becoming anaerobic; thus involving excessive handling costs in aeration by turning, and requiring an extended composting period. In some instances the maximum practical height may be governed by the equipment used for stacking, or by a tendency of the pile to get excessively hot—above about 70°C. If the pile is too shallow heat loss may be excessive and optimum temperatures for thermophilic organisms may not be achieved. A maximum height of 5 or 6 feet and a minimum of 4 feet is recommended for freshly ground municipal refuse. As the pile shrinks during decomposition the desired height can be maintained by reducing the width of windrow at the time it is turned.

For convenience in turning, the initial width of the windrow will probably not exceed 8 or 10 feet if the cross-section is made trapezoidal. If the top is rounded to shed water, the width may be governed by permissible maximum height. Suitable dimensions of the pile to meet conditions of weather, equipment used in stacking and turning, and daily tonnage processed will, of course, be developed with experience in each individual case.

Aeration by Turning.--Conditions necessary for rapid aerobic decomposition of organic matter are maintained by periodically aerating the composting material. The simplest method of aerating a compost pile is by turning as often as necessary to prevent development of serious anaerobic conditions. An anaerobic condition usually results from a moisture content too great for the normal turning schedule adopted. Excess moisture may be inherent in any particular refuse, or it might result from continual soaking by rain. Anaerobic conditions may develop also as a result of equipment breakdown or other interruption of a normal turning schedule, or during a long period of unusually bad weather; but whatever the cause such conditions will disappear under frequent aeration of the pile by turning.

The frequency of turning and the total number of turns required during the composting process are governed largely by the moisture content.

Experience at Berkeley indicates that for municipal refuse the following turning schedule is adequate:

1. If initial moisture is more than 70 percent, turn daily until moisture is reduced to less than 70 percent. Then follow schedule in Table 6.
2. If initial moisture is less than 70 percent, make first turn on third day. Thereafter follow schedule in Table 6 until 11 or 12 days have elapsed.

TABLE 6

RECOMMENDED SCHEDULE OF TURNING IN RELATION TO INITIAL MOISTURE CONTENT OF MATERIAL

Moisture Content	Turning Schedule	Approx. Total No. of Turns Required	Other Treatment
Less than 40%	--	--	Add moisture; then follow schedule for higher moisture content
40 to 60%	3-day intervals	3 or 4	
60 to 70%	2-day intervals	4 or 5	

In pursuing the foregoing schedule it is not necessary to determine moisture after the initial analysis. Experience soon teaches the operator to recognize the need for adding moisture or for increasing the frequency of turning. A good rule of thumb is to begin a schedule of daily turning if a foul odor is evident when a pile is disturbed either by turning or by digging into it for inspection purposes; and continue daily turning until the odor no longer is evident. Inasmuch as turning will reclaim an anaerobic compost it can be omitted on weekends and holidays if additional costs are involved without permanent injury to the compost.

Uniform decomposition is essential to rapid composting. To insure this it is necessary that the outer edges be turned into the center of the pile at each turn. Such an inward mixing exposes any fly larvae, pathogens, or insect eggs which might survive at the cooler surface to the lethal temperatures of the interior of the pile. Specialized machinery for accomplishing such turning has not been developed in the United States, but the problem would not be particularly difficult to solve if there was a demand for such a device.

West Foods, Inc., at Soquel, California, employs a modified Barber-Greene self propelled over-cab loader in turning a compost of manure and straw for use in growing mushrooms.

A self propelled machine similar to a modern twin-helix snow plow equipped with a windrow shaping device would seem to have great possibilities for turning a compost stacked in the open.

Judging the Condition of a Compost.--In a compost pile in which aerobic decomposition progresses in a typical manner the temperature follows the orderly course previously described--a rapid initial rise to 60-70 degrees

in 3 or 4 days; a period of sustained high temperature; and a temperature recession. Temperature alone, however, is not a sufficient indicator of the situation inside a composting mass as a temperature decline may result from the development of conditions unfavorable to aerobic thermophiles either through excessive heat, the onset of anaerobic conditions, or the lack of sufficient moisture. If a thermal kill is responsible for a decrease in temperature, temperatures appreciably above 70°C will have obtained for some time prior to the decrease. Anaerobic conditions are quite easily detected. A putrefactive odor especially noticeable when the pile is disturbed indicates the need of aeration. Besides, the material inside an anaerobic pile has an easily recognizable pale green, faintly luminescent color that shows little change from day to day, whereas properly developing aerobic compost is characterized by a progressively darkening color. Generally the anaerobic mass is excessively moist and foul smelling drainage liquors may appear. Lack of moisture is likewise easily detected by the human eye. The observer quickly learns to tell by a visual inspection when added moisture is needed.

A dropping temperature which is not due to thermal kill, oxygen shortage, or low moisture, and which follows a typical sustained temperature plateau is a good indication that the compost is finished. Since bacterial die-away is greater than temperature drop would indicate, because of the insulating qualities of the pile, the compost may generally be considered finished when the declining temperature reaches 55 or 50°C.

Characteristic changes in odor during the period of composting may aid in judgment. Grinding or shredding serves to replace the sour greasy odor of raw garbage with an odor generally associated with freshly cut green vegetation. As temperature increases cooking odors develop; then disappear as stabilization progresses. A slight odor of ammonia may persist, or become quite pronounced in a compost which is losing nitrogen. Finally the material may be free of odor, or have a slightly earthy or moldy odor.

Color is a poor indicator of the condition of a compost which has not become anaerobic inasmuch as the appearance of rich dark soil is achieved long before stabilization has been accomplished. Some processes purported to produce a finished compost in 3 days or less (11) achieve very little stabilization but produce a material having a good odor.

The change in C/N ratio is a good criterion of the degree of stabilization accomplished by composting, especially when the increase in percentage ash is also observed. Unfortunately, it is not easily determined in the laboratory because of the difficulty of running the necessary test for carbon. New Zealand researchers (11) have suggested an approximate equation:

$$\% \text{ Carbon} = \frac{100 - \% \text{ ash}}{1.8}$$

The field studies showed this to be accurate within 2 to 10 percent and it is therefore recommended as sufficiently accurate for practical composting.

Familiarity with the time normally required for composting in a particular operation, or in general, is useful in judging the course of a compost. The higher the C/N ratio of a material, the longer the period required for stabilization. The relation between composting time and C/N ratio observed at Berkeley for mixed municipal refuse having a moisture content below 70 percent are as follows:

Initial C/N ratio, 20; composting time, approximately 12 days.
Initial C/N ratio, 20-50; composting time, approximately 14 days.
Initial C/N ratio, 78; composting time, approximately 21 days.

For other materials the composting time varies with the nature of the material and the composting method.

Some observed composting times for various materials and composting processes are presented in Table 7.

TABLE 7

Material	Reported by	Time	Conditions
Mixed Municipal Refuse	U. of Calif.	12 to 21 days	Field
Garbage plus straw	" " "	5 - 9 days	Pilot Plant
Garbage plus manure	" " "	5 - 9 days	" "
Garbage plus sewage sludge	" " "	12 - 16 days	Field
Selected garbage plus sewage sludge	Frazer, N.Y.	7 days	Field
Mixed Municipal garbage, etc.	Dannevirke, N.Z.	20 - 30 wks.	Field
Air dry refuse and Night Soil, etc.	Ficksburg, S. Africa	30 days in pit, "ripen" 4 - 6 wks.	Field
Selected refuse and sewage sludge	Domfriesshire Gr. Britain	6 wks. composting, 6 wks. maturation	Field
Grass Clippings	U. of Calif.	11 - 14 days	Pilot Plant
Municipal Refuse (no garbage)	Holland	3 to 6 wks. 4 to 6 months	Production

Remilling of Compost.--In the interest of appearance and ease of application of compost to the soil, it is desirable to regrind the finished product. Finished compost is much easier to grind than is raw refuse. At Berkeley, finished compost with a moisture content of 55 percent was reground without any difficulties in the hammermill. A screen with 3/8-inch openings was found to be most satisfactory. The amount of material to be ground after composting is somewhat less than the original weight of refuse. In the field studies the yield was from 70 to 80 percent based on the dry weight of the compostable fraction of municipal refuse, although the loss in volume amounted to 50 percent or more. The yield from plain vegetable trimmings and straw used in the pilot studies was somewhat lower, averaging from 50 to 60 percent.

The Value of Compost

The value of compost may be expressed in two mutually dependent ways—its intrinsic value to the soil, and the dollars-per-ton price at which it can be sold at a profit to private enterprise or at a loss to the community no greater than the cost of alternate disposal methods.

The value of compost to agricultural soils lies both in fertilizer and trace elements and in the unique ability of humus to:

1. Improve soil structure, thus increasing its water retention capacity and encouraging more extensive development of root systems of plants.
2. Form a complex with inorganic phosphate, making it more readily available to higher plants.
3. Tie up nitrogen in bacterial protoplasm, thus preventing its leaching away and making its rate of availability more nearly equal to the rate at which plants can utilize it.

The fertilizer and other constituents of the compost made at Berkeley from various materials are shown in Table 8.

The dollar-per-ton price at which compost can be produced and sold is a matter of speculation. A careful analysis of the processes advocated in the United States based on such data as are available and on preliminary design estimates indicates that compost might eventually be produced and sold at a modest profit at about 15 dollars per ton of finished compost, provided that:

1. The present cost of collecting refuse and hauling it to the disposal site is not considered a part of the cost of production.
2. The profits from salvage accrue to the composting operation.
3. The composting operation is on a scale beyond the economic break point (probably 100 tons raw material per day).
4. The yield of compost on a dry weight basis is about 70 to 80 percent of the compostable fraction of municipal refuse, as observed at Berkeley.
5. That large scale agriculture will accept the product at such a price, as would seem to be the case in California.

Problems of Municipal Composting

It is impossible to predict whether composting will become widely accepted as a method of refuse disposal in the United States although for many communities it seems to offer good possibilities. Interest on the part of public officials is considerable at the present time and there is a widespread and growing feeling among citizens that our nation cannot continue to prosper indefinitely without reclaiming its organic wastes and returning them to the soil. As evidence they point to the experience of older segments of the earth. Realistically, however, it must be recognized that the need for solving refuse disposal problems is acute and immediate in many communities while the need for reclamation of organic matter is more speculative. Meanwhile the whole economy of composting hinges on the value of the material reclaimed and, in spite of hopeful examples, composting has not yet been put on a sound economic basis on a city-wide scale in the United States.

In the absence of accurate knowledge of the economics of compost production and of the public acceptance of the product, municipal officials are understandably reluctant to embark on a composting program. There are other factors that contribute to this hesitancy. For example, public officials desire a process which is not expected to involve the city in a program of experimentation and development.

There are no mechanized composting plants in the United States of demonstrated performance on a municipal scale from which an economical design might be developed. It is believed, however, that a plant could be designed by engineers experienced in other types of materials handling which would function satisfactorily with only minor modifications after the beginning of operations.

TABLE 8

FERTILIZER AND OTHER CONSTITUENTS OF COMPOST MADE FROM VARIOUS MATERIALS

Material	Nitrogen Percent	Phosphorus Pentoxide Percent	Potassium Oxide Percent	Carbon Percent	Ash Percent	C/N Ratio
Municipal Refuse	1.63	0.96	0.87	30.84	29.20	19.0
" "	1.44	0.78	1.01	28.75	42.10	19.0
" "	1.32	1.20	0.84	32.55	40.84	24.0
" "	1.21	1.87	0.84	28.08	51.07	23.0
" "	1.24	1.10	0.53	24.43	39.42	19.0
" "	1.02	1.36	0.72	29.64	37.59	29.0
" "	1.24	1.10	0.53	24.43	39.42	19.0
" "	0.90	0.90	0.65	31.90	37.04	35.0
" "	0.97	0.73	0.51	23.51	26.64	24.0
Municipal refuse and 4%* raw sewage sludge	1.20	0.60	1.39	24.56	38.02	20.3
Municipal refuse and 6%* digested sewage sludge	1.10	1.06	1.39	27.30	45.30	22.7
Municipal garbage and 5.5%* pear wastes	1.33	1.24	1.06	25.68	45.69	19.0
Municipal garbage plus 10% soil	1.02	1.10	0.94	20.71	63.85	20.0
Grass clippings	1.97	2.29	3.95	28.40	40.68	14.4
Misc. garden and kitchen refuse	1.58	1.37	1.15	26.10	41.32	16.5
Vegetable trimmings and paper	1.32	0.60	1.43	36.59	16.91	26.1
Vegetable trimmings and paper	1.57	1.84	0.96	38.30	20.0	24.4
Vegetable trimmings and paper	1.22	1.28	1.48	30.72	20.86	26.4
Vegetable trimmings and 2% horse manure	2.01	1.88	4.52	37.44	20.12	18.6

* Based on dry weight of materials

There is little doubt, therefore, that when some city or private enterprise becomes seriously interested in exploring the possibilities of composting a study of the engineering economics involved in the process will not be long in forthcoming.

In the meantime, general good judgment on the parts of engineers and public officials has prevented communities from embracing unsound and untried processes from which the profit to the promoter is to come from royalties rather than from the sale of compost. Nevertheless, the difficulty of discerning the sound proposal inevitably delays the acceptance of composting as a refuse disposal method.

Under the existing conditions city officials would be pleased for private enterprise to enter into commercial composting of the city's refuse, and would probably grant the long term right to publicly owned raw materials which industry would need to make a composting project profitable. There would seem to be a good field for risk capital in such a venture, although it may well be that some of the cost of development will have to be borne by the public.

There seems little likelihood that composting can be expected to pay the cost of collecting and transporting refuse. In many large cities, for example in New York, it is possible that space requirements and distance from markets for the product might rule out the process altogether. But there is good reason to believe that a process such as defined by these studies offers an economical and sound solution to the refuse disposal problems of many communities, at the same time reclaiming a material of immense value to agriculture.

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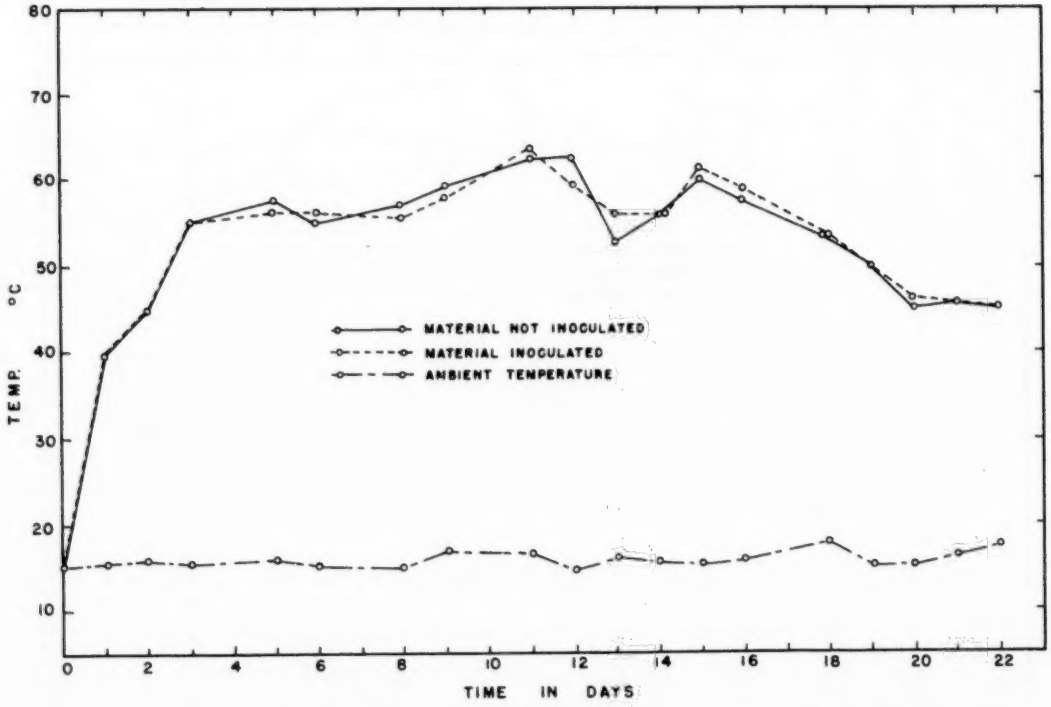

Fig. 1. Temperature Curves Showing Similarity Of Inoculated And Uninoculated Aerobically Composting Material

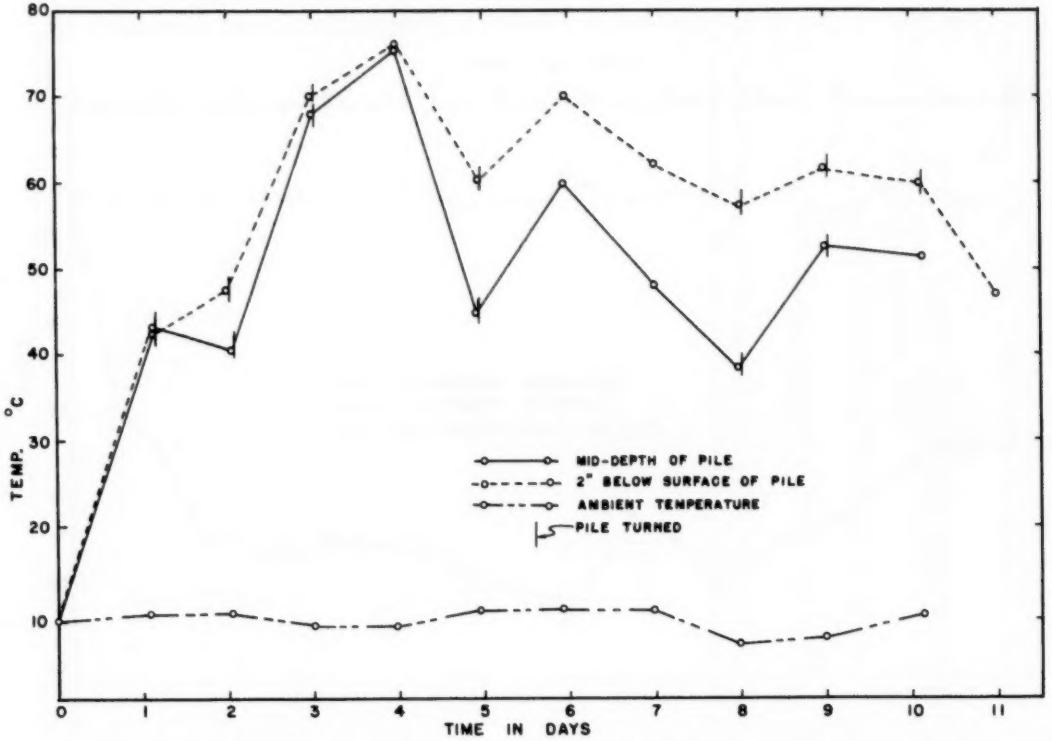

Fig. 2. Curves Showing Temperature Plateau Typical Of A Small Mass Of Aerobically Composting Material; Also Results Of Inadequate Aeration During Composting Period.

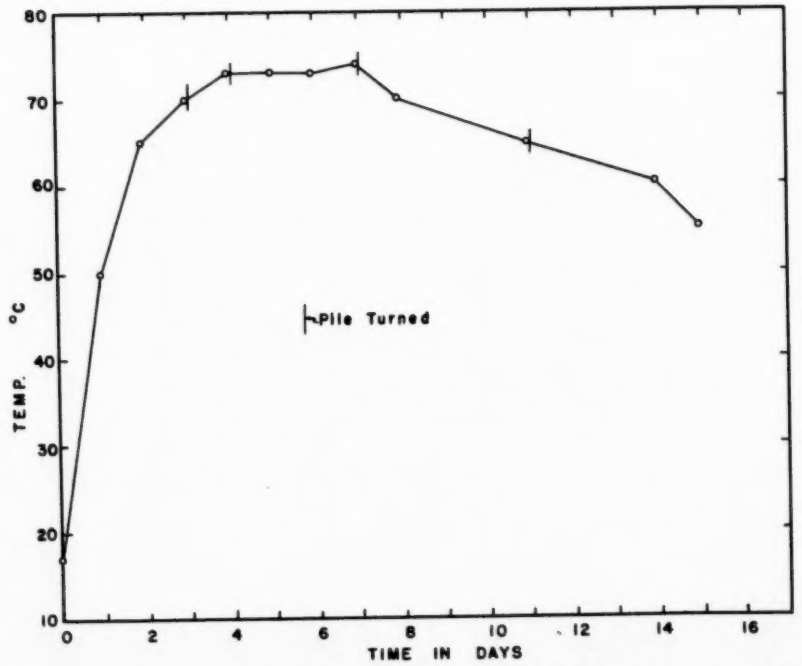

Fig. 3. Temperature Curve Typical Of A Large Mass Of Aerobically Composting Material.

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